OPTIMAL LAND COVER MODEL AND ECOLOGICAL BACKGROUND OF THE MEDIEVAL SETTLEMENTS IN THE CSÓKAKŐ DOMAIN

A CSÓKAKŐI URADALOM KÖZÉPKORI TELEPÜLÉSEINEK OPTIMÁLIS FELSZÍNBORÍTOTTSÁGI MODELLEZÉSE ÉS KÖRNYEZETI HÁTTERE•

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Abstract

The combined analysis of archaeological settlement networks and environmental conditions has significantly enhanced our understanding of past societies and their interaction with a changing environment. This study seeks to explore a new methodological approach for visualising and modelling the optimal land cover of a microregion. The starting point was the Second Military Survey of the Habsburg Empire, which provided spatially accurate land cover data for the area of the former medieval Csókakő domain, located in Fejér and Veszprém counties.

A detailed GIS analysis of environmental variables—including pedology, geology, topographic wetness index, aspect, and landform classification—and the application of the Analytic Hierarchy Process (AHP) for weighting resulted in probability maps for the various land cover types within the study area. A primary optimal land cover model, forming the basis for a geographically induced land cover model, was created by selecting, for each 25 × 25 m cell, the land cover type with the highest probability value.

*The results of the land cover patterns in the 1,500-metres buffer zones around known medieval settlements were also compared with data from a common valuation estimation (*aestimatio communis*) dated 1493, which contains detailed information on Late Medieval land use in these areas.*

Kivonat

*A régészeti településhálózatok és a természetföldrajzi környezetre vonatkozó adatok együttes értelmezése nagyban kitágította az egykori közösségek megértését egy folyamatosan változó környezetben. Jelen tanulmány célja egy mikrorégió optimális felszínborítottságának modellezése és megjelenítése egy új módszertani megközelítéssel. A modellezés kiindulópontja a Második Katonai Felmérés volt, amely az egykori csókakői uradalom területéről pontos felszínborítottsági adatokat szolgáltatott. A környezeti fedvények (talajtan, geológia, vizesség index, kitettség, felszínformák) részletes térinformatikai elemzése és az Analytic Hierarchy Process módszer adatsúlyozási felhasználása az egyes felszínborítottsági típusokról a kutatási terület egészén külön-külön egy valószínűségi térképet eredményezett. A különböző felszínborítottsági valószínűségi térképek közül a legmagasabb értékűt kiválasztva létrejött a 25 × 25 méteres felbontású elsődleges optimális felszínborítottsági modell. A modellezési eredmények tesztelése a csókakői uradalom ismert középkori településeinek 1500 méter sugarú buffer zónájában található felszínborítottsági típusok megoszlásának és az 1493-as közbecsűben (*aestimatio communis*) található településekhez tartozó művelési ágak területi összevetésével valósult meg.*

KEYWORDS: GIS ANALYSIS, LAND COVER, MEDIEVAL SETTLEMENT PATTERN, OPTIMAL LAND COVER MODELLING

KULCSSZAVAK: TÉRINFORMATIKAI ELEMZÉS, FELSZÍNBORÍTOTTSÁG, KÖZÉPKORI TELEPÜLÉSHÁLÓZAT, OPTIMÁLIS FELSZÍNBORÍTOTTSÁGI MODELLEZÉS

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Introduction

The simultaneous study of long-term archaeological settlement patterns and environmental changes have proven highly beneficial over recent decades, significantly advancing our understanding of past societies and their interactions with the natural world. An important kind of investigation is land cover and land use change (LCLUC), which is increasingly attracting the attention of historians and archaeologists alike (Chang-Martinez et al. 2015; Hughes et al. 2018; Morisson et al. 2021; Sugita 2007).

The analysis of pollen and multi-proxy palaeo-ecological data has provided valuable insights into how human activity has shaped the landscape, while also shedding light on the ways in which changing environmental conditions have both necessitated and constrained human adaptation. Although such datasets often provide a micro-regional overview of long-term processes, their spatial extent and resolution are inherently limited by the nature of pollen accumulation and the methods of data collection (Deza-Araujo et al. 2022; Füzesi et al. 2006; Magyari et al. 2012; Sümegi et al. 2005; Trondman et al. 2015; Vareilles et al. 2021).

Our methodology is based on the premise that land cover patches within the landscape are shaped by both environmental and human influences. This enables the analysis of the spatial distribution of different land cover types—such as forests, pastures, arable lands, or wetlands—on an individual basis (Apronen et al. 2019; Lespez 2025). The general aim of these optimal land cover (OLC) calculations is to assess the environmental characteristics of each land cover type through a Geographic Information System (GIS)-based approach, resulting in individual land cover probability maps. Naturally, swamps and wetlands are expected to occupy low-lying areas, arable lands to be situated on higher ground, and mountainous zones to be predominantly covered with forests and, to some extent, pastures (Andrásfalvy & Vargyas 2009). The separate modelling of these land cover types as probability maps enables pixel-level comparison at a microregional scale.

In this study, we focus on the area of the former medieval Csókakő Castle domain in Fejér County, Central Hungary, to explore and identify potential land cover changes between the Middle Ages and the Modern Period. Based on the modelled results, we also examine the economic contributions of the settlements to the structured life of the domain.

Study area and datasets

Study area

The main castle and centre of the later domain in Csókakő was founded by the Csák kindred in the second half of the 13th century on the southern slopes of the Vértes Mountains. Later, in the 14th–16th century, it was owned and developed by kings and noble families like the Rozgonyis, the Kanizsais, the Nádasys, and the Bakics. The castle and the domain became occupied during the 1543–1544 Ottoman military campaign and remained under Ottoman rule until 1687, except for a few years during the Long Turkish War in 1593–1606 (Hatházi 2010; Hatházi & Kovács 2019; Bocsi et al. 2023).

Csókakő Castle lies approximately 25 km north of the medieval royal town of Székesfehérvár. Once it controlled a section of the pilgrimage road from Western Europe to Jerusalem between Győr and Székesfehérvár and some adjacent military and trade routes. Based on written sources, the most active period of the domain was between 1430 and 1511: fifteen charters and estimations from this period mention about 32 permanently or temporarily inhabited settlements, villages and partial estates in the medieval Fejér and Veszprém counties (Bocsi 2006; Bocsi 2007; Hatházi 2010; Bocsi et al. 2023); of these, only 24 has been identified with archaeological methods (with varying spatial accuracy).

The 1,458 km^2 study area was defined based on the all-time largest extent of the former Csókakő Castle domain by fitting and merging a 5 km buffer zone around the known medieval settlements, which is roughly an hour walk by foot. The microregion is comprised of parts with diverse terrain, including wetlands and swamps in the Mór Ditch, south of the Vértes Mountains, and the close vicinity southwest of Lake Velence, the Vértes and Bakony Mountains emerging in the north, and hills north of Lake Velence and northeast of the Vértes Mountains (Dövényi 2010). The locations of the medieval archaeological sites were determined based on data obtained from the Hungarian National Site Registry; each site is marked with its centroid point on the map (**Fig. 1.**).

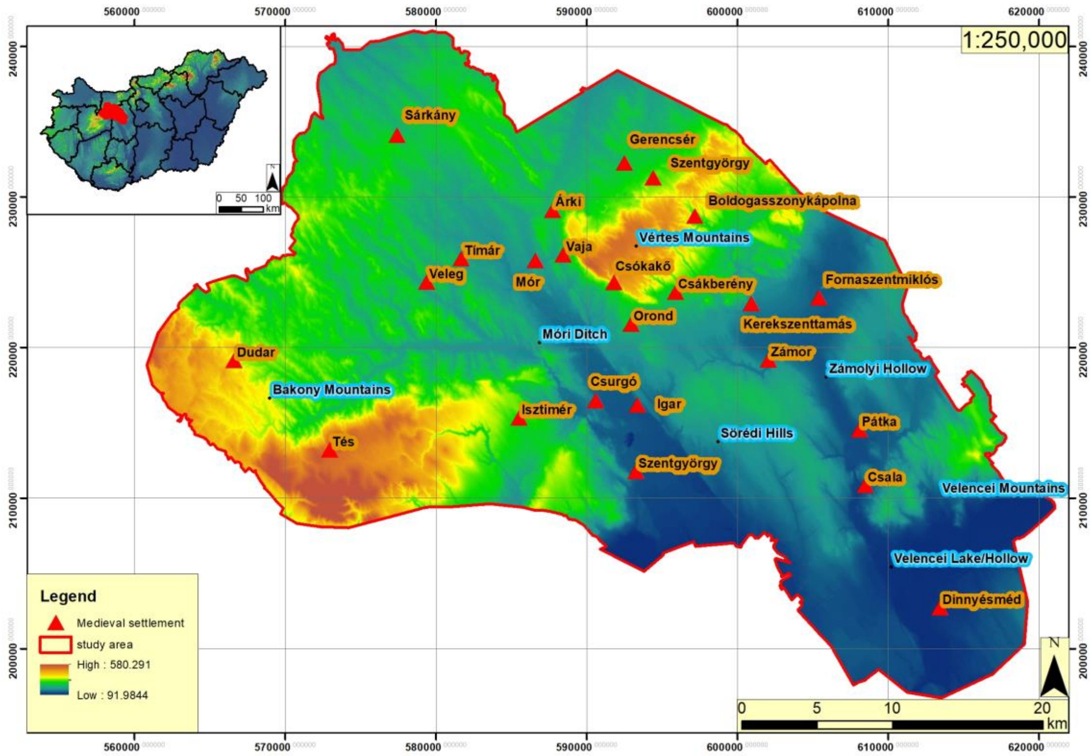

Fig. 1.: DEM of the study area with microregions and the medieval settlements of the Csókakő domain

1. ábra: A vizsgálati terület domborzatmodellje, tájegységei és a csókakői uradalom középkori települései

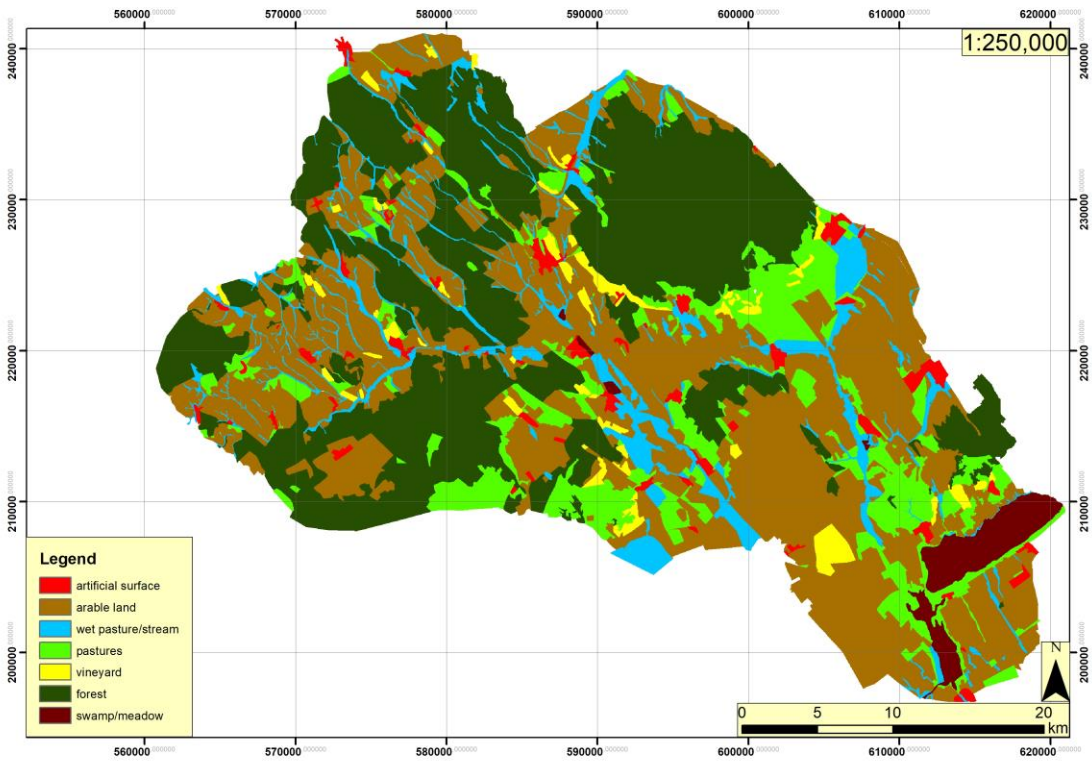

Fig. 2.: Land cover categories of the Second Military Survey

2. ábra: A Második Katonai Felmérés felszínborítottsági kategóriái

Environmental datasets

Basic land cover data for the microregion were collected from the Second Military Survey of the Habsburg Empire, which may be considered the first countrywide survey programme in the Kingdom of Hungary with the spatial accuracy and a unified land cover template suitable for modelling purposes (Arcanum 2005; Jankó 2007, 62–63). Conducted across the kingdom with varying intensity between 1819 and 1869, the survey covered most of the study area in 1847 (Jankó 2007, 186). The duration of cadastral fieldwork and the application of a known geodetic data-gathering system far surpassed the detail and spatial accuracy of the First Military Survey. Moreover, the Second Military Survey in the microregion was conducted largely prior to the major water regulation projects of the 19th century (Jankó 2007, 62–63).

During the digitisation of the georeferenced dataset from the Second Military Survey, arable land, pastures, wet pastures or streams, forests, swamps, vineyards, and artificial areas were separated and vectorised into a shape file. Arable lands (40.42%) and forests (33.49%) dominated the mid-19th-century landscape. Pastures (12.02%) and wetlands and streams (7.22%) were also significant, while vineyards, artificial areas, and swamps each occupied only 2–3% of the microregion (**Fig. 2**).

The environmental properties of the land cover classes were extracted from specific GIS layers. The 1-metre interval contour lines were derived from the 5 × 5 m digital elevation model (DEM) of Hungary. Following smoothing, the *Topo to Raster* script (https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/topo-to-raster.htm, last accessed on 24.04.2025) was used in ArcMap 10.4 to generate a new DEM with a resolution of 10 × 10 m. Aspect (https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/aspect.htm, last accessed on 24.04.2025) and landform classification (Jenness 2013) layers were derived from this updated DEM, while Topographic Wetness Index calculations were performed in SAGA GIS (https://saga-gis.sourceforge.io/saga_tool_doc/2.1.3/ta_hydrology_20.html, last accessed on 24.04.2025).

The pedology layer was obtained from the AGROTOPO database (http://maps.rissac.hu/agrotopo/, last accessed on 24.04.2025), and geological data were sourced from the MÁFI database (https://map.hugeo.hu/fdt100/, last accessed on 24.04.2025). All environmental layers were classified into integer-type formats and converted into standardised 25 × 25 m raster datasets.

Modelling process

Data collection

A regular point grid was fitted over the study area by aligning the gridded points into the centre of the 25 x 25 m raster cells of the environmental layers, comprising approximately 2,300,000 points. The land cover types from the digitised Second Military Survey maps and all environmental data were linked to each point through spatial joining.

A multi-scalar approach was employed to gain a comprehensive understanding of the environmental characteristics associated with the various land cover types. A 100 × 100 m regular point grid, consisting of around 143,000 points, was laid on the study area, and spatial joining was used to aggregate data from the combined 25 × 25 m point grid within 30-, 200-, and 500-m buffer zones. Next, the multi-scalar results were separated by land cover type and the distribution of the environmental layer categories were calculated in each case. The environmental layer's overall distribution within the whole study area was calculated by categories and compared with the multi-scalar results for each land cover type to define its most likely occurrences within the study area.

Data weighting

Positive and negative predictor categories of environmental layers were identified by determining the variance between the general and individual distribution values for each land cover type. As these values differed for every land cover type, the weight values for each were defined independently through a multi-level weighting process.

A slightly modified version of the Analytic Hierarchy Process (AHP) was implemented for weighting. AHP is a widely used multi-objective decision-making method that integrates qualitative and quantitative datasets to provide a comprehensive understanding of large, complex systems (Saaty 1977; Saaty 1980; Saaty 1987; Saaty & Vargas 2006). In this method, data is structured into a logical hierarchy, which is subsequently assessed at each level by breaking down the decision-making process into smaller components. Based on expert judgement – or in our case, measured data – the method involves ranking the importance of each variable on a scale from 1 (least important) to 9 (most important) at every level and within each group, using pairwise comparisons between all variables (Saaty matrix) to determine each element's weight. AHP allows for the management and organisation of different hierarchy levels by weighting them within a unified, closed system.

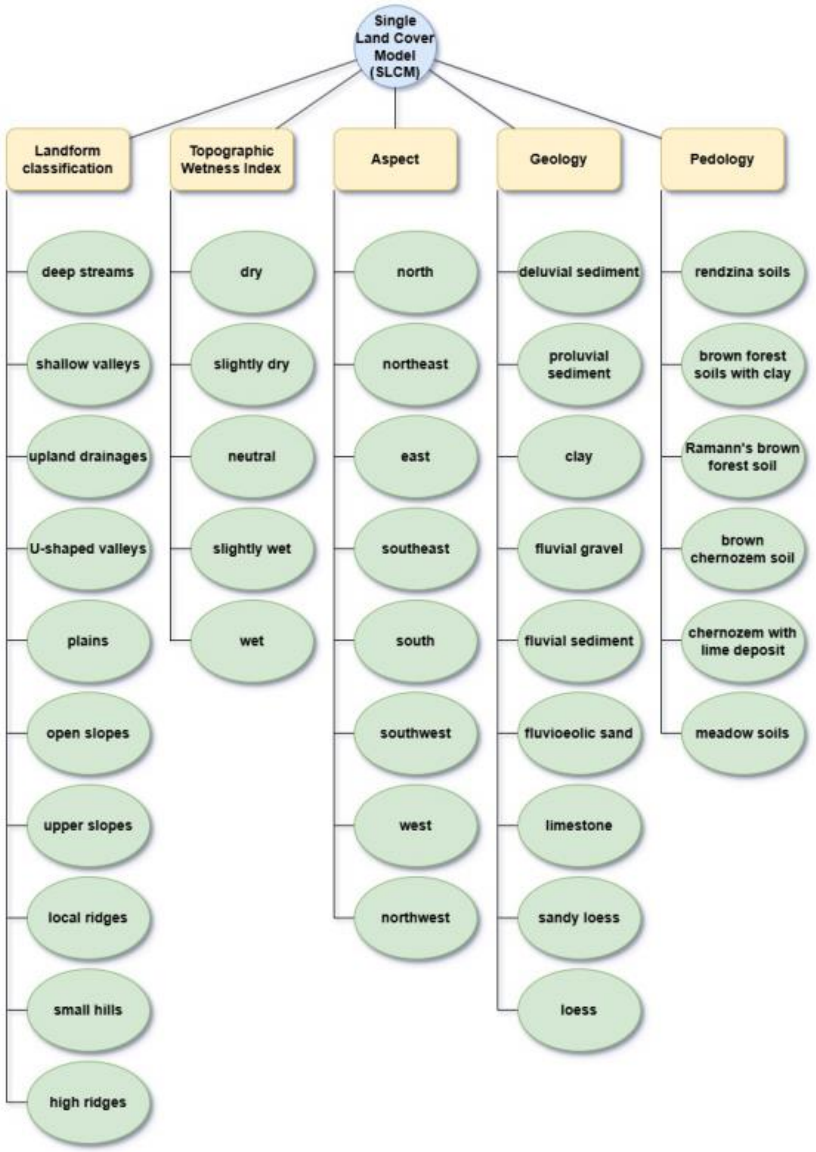

Fig. 3a: Lower and higher hierarchy levels (AHP) of weighting in the optimal land cover model

3a ábra: Az optimális felszínborítottsági modellezés súlyozása az alsó és felső hierarchikus szinteken (AHP)

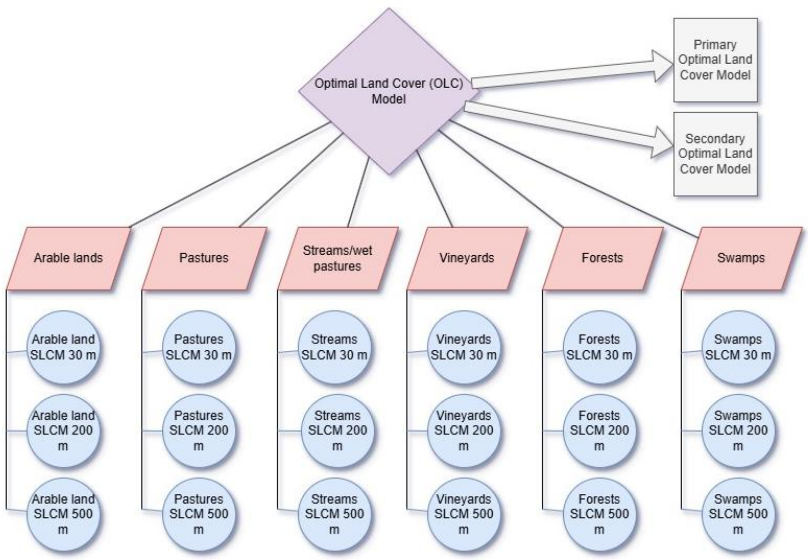

Fig. 3b: Data structure of the optimal land cover model

3b ábra: Az optimális felszínborítottsági modell adatszerkezete

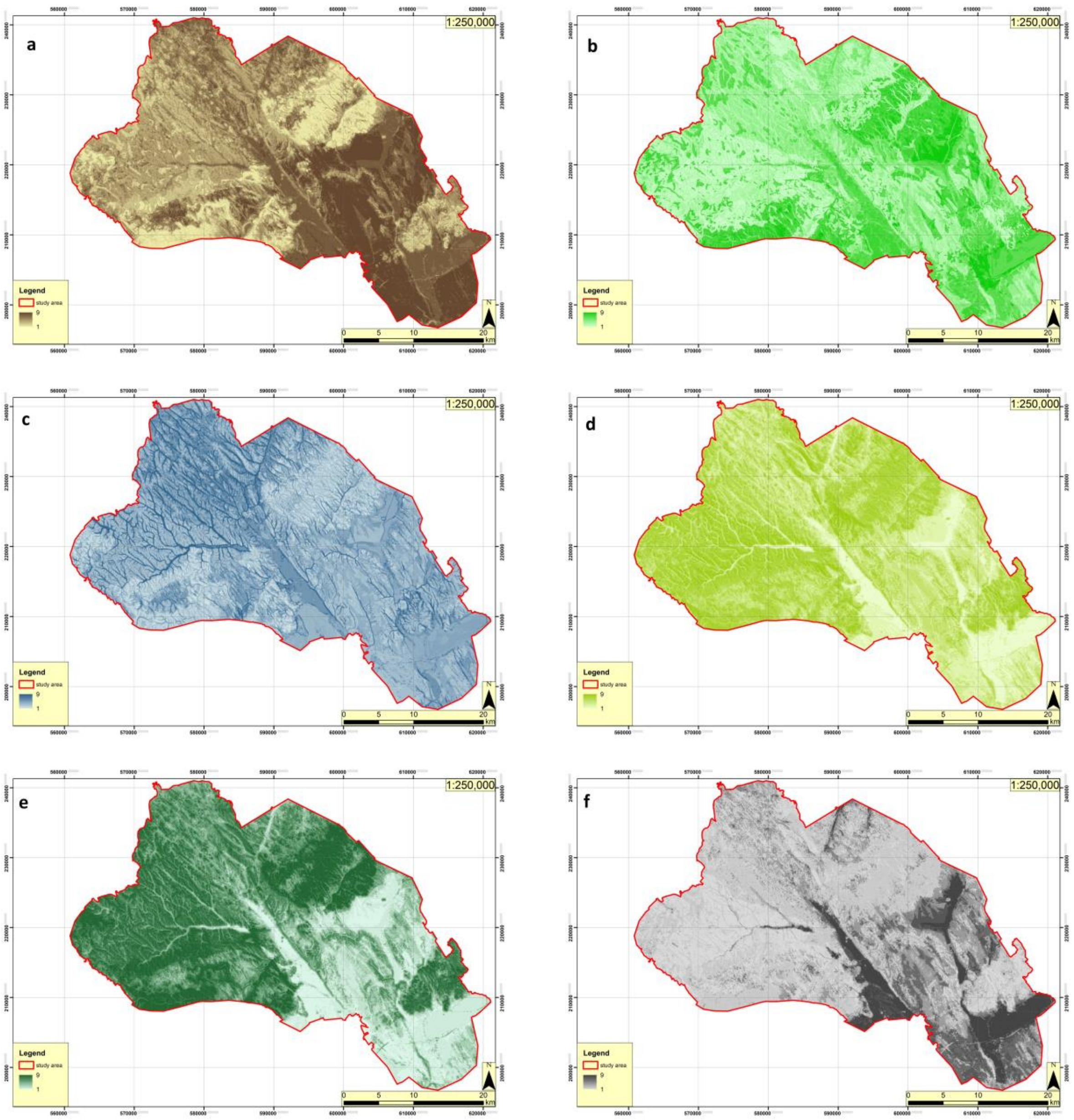

Fig 4.: Optimal land cover probability maps for a, arable land, b, pastures, c, streams and wet pastures, d, vineyards, e, forests, f, swamps

4. ábra: Optimális felszínborítottsági valószínűségi térképek szántóterületekhez a, legelőkhöz b, vízfolyásokhoz és vizes gyepekhez c, szőlőkhöz d, erdőkhöz e és mocsaras területekhez f

In our case, a two-level weighting approach was applied. Data related to every environmental layer category were weighted separately on the lower level, and the relative importance of the environmental layers themselves within the model was assessed on the higher level. At the lower level, the general distribution of each environmental layer's category was defined for the whole study area, as well as the unique distribution for each specific land cover type. The two values were then subtracted from one another. The largest negative and positive difference values were assigned weights of 1 and 9 respectively, regardless of the overall range of variance, while intermediate values were calculated proportionally and rounded to whole numbers. Through these calculations, the overall range of variance of the environmental layer categories (lower hierarchy level) determined their own overall weight values at the higher hierarchy level. As such, greater data variance and significant deviation from the general distribution resulted in a higher overall weight.

This process concluded in the creation of a Single Land Cover Model (SLCM) (**Fig. 3a**) (Khaira & Dwivedi 2018; Nicu 2016; Saaty & Vargas 2006;

2012; Whitaker 2007). The procedure was repeated for each of the six land cover types across the multi-scalar buffer zone datasets at 30-, 200-, and 500-metres scales, producing a total of 18 sub-SLCMs (**Fig. 3b**).

The results of the two-level weighting process were integrated into the *ArcMap Weighted Overlay* tool (https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/weighted-overlay.htm; last accessed on 24. 04. 2025) to visualise the probability of the spatial occurrence of each land cover type across the entire study area. The resulting probability maps for each land cover type were combined using a 50%–30%–20% weighting ratio for the 30 m, 200 m, and 500 m buffer zones, respectively, thereby assigning greater importance to the smaller (more localised) buffer zones.

These individual maps, scaled from 1 to 9 in accordance with the AHP calculations, highlighted areas of higher and lower suitability for each land cover type (**Fig. 4**). The unified weighting approach also enabled the construction of a comprehensive Optimal Land Cover (OLC) model for the study area by selecting, for every 25 × 25 m pixel, the first (primary) and second (secondary) most probable land cover types (**Figs. 5–6**).

As a final step, 1,500 m and 5,000 m buffer zones were clipped from the primary OLC maps around the 24 known Late Medieval settlements, in order to analyse their immediately accessible surroundings and their broader ecological niche reachable within a typical daily round trip (Bintliff 2002; Chisholm 1979a; Simon 2022).

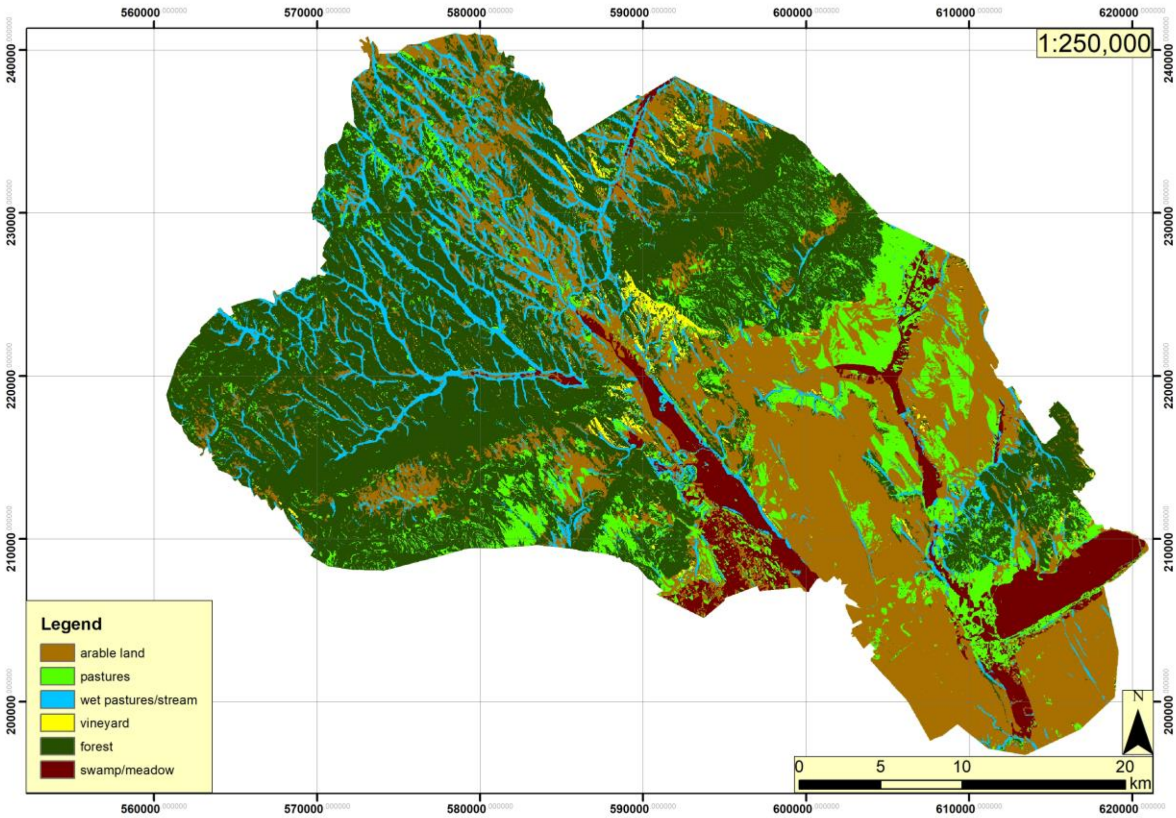

Fig. 5.: Primary optimal land cover map of the study area

5. ábra: A vizsgálati terület elsődleges optimális felszínborítottsági modellje

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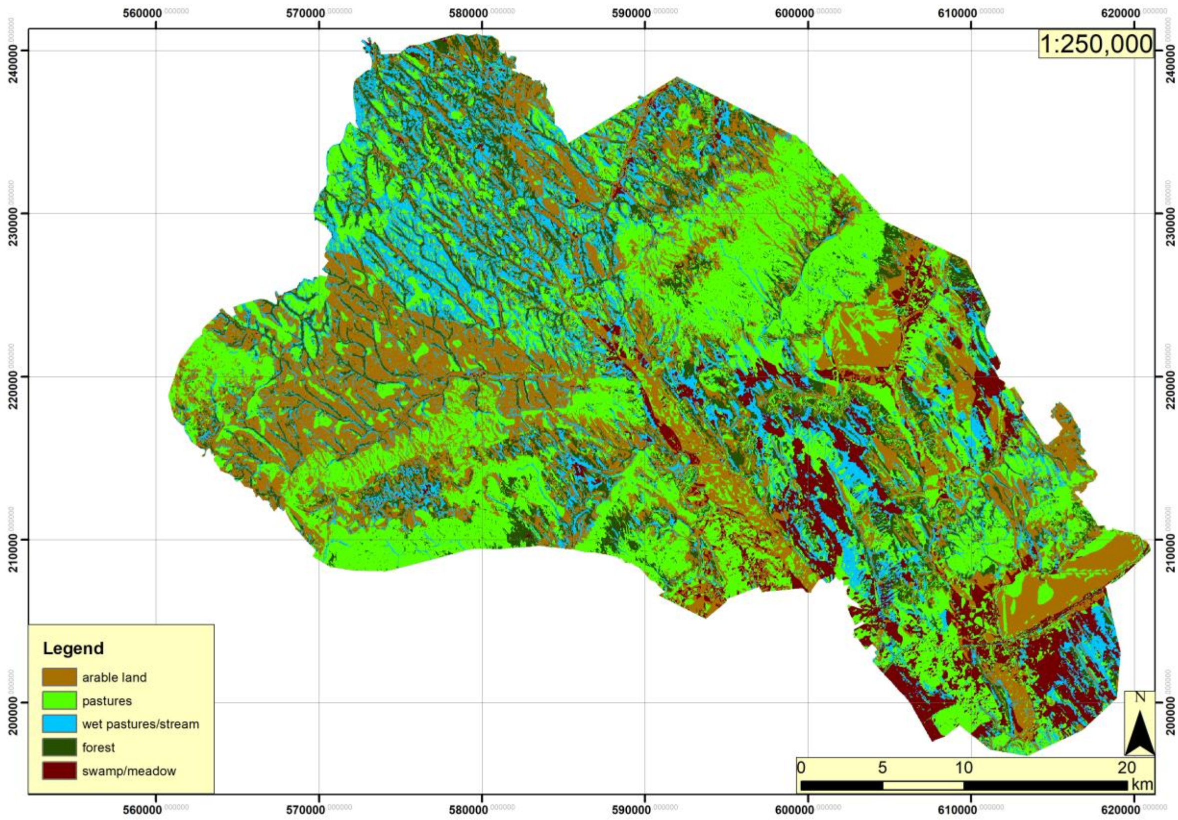

Fig. 6.: Secondary optimal land cover map of the study area

6. ábra: A vizsgálati terület másodlagos optimális felszínborítottsági modellje

Modelling results

The Second Military Survey and the optimal land cover models

The distribution of different land cover types on the Second Military Survey and the primary OLC map coincided in only 53.02% of the study area, although the overall proportions of the land cover types were broadly similar. Significant differences were primarily observed in the reduction of arable land and the increase in forested areas in the OLC model (**Table 1**). The spatial overlap between the land cover types across the two datasets revealed distinct patterns. While 93.4% of swamp areas were identical in both datasets, only 75.4% of forested areas, less than 50% of arable land, and under 30% of pastures, wet pastures, or stream-related zones showed similar spatial distributions (**Figs. 7–8**).

Arable land between Lake Velence and the Vértes Mountains occupied similar spatial positions in both datasets, whereas in the Söréd Hills, Velence Mountains, and Zámoly Basin microregions, significant areas were converted into pastures or forests. In the Bakony Mountains, arable land was predominantly modelled as forests. Large pasture areas near the Bakony, Velence, and Vértes Mountains were similarly reclassified as forests, while the wet pastures of the Mór Ditch and areas south of the Vértes Mountains were reinterpreted as swamps by the OLC model. The primary wine-producing zones were identifiable on the southern slopes of the Vértes Mountains; however, vineyards depicted in the Second Military Survey were mostly represented as forested areas in the Bakony Mountains. Although these zones occasionally included small clusters of modelled vineyard pixels, this was inconsistent.

The extent of forests remained largely unchanged between the two datasets in the mountainous regions, though smaller patches of pasture and arable land appeared, contributing to a more mosaic-like landscape.

The Second Military Survey and the secondary OLC model showed identical land cover across 22.33% of the study area, with a more fragmented spatial pattern than the primary OLC model. When combined, the primary and secondary OLC models achieved a 75.35% match with the Second Military Survey within the study area.

Additional discrepancies appeared in the Mór Ditch and the region between the Vértes and Velence Mountains, where wet pastures were primarily modelled as dry pastures or meadows. Vineyards associated with settlements across the study area tended to be modelled as either forests or arable land. The stream network in the Bakony Mountains also became more prominent in the modelling process, with forests, pastures, and arable lands frequently differing in small patches between the two datasets (**Figs. 7c, 8–9**).

Land Cover and the economic role of the medieval and Early Modern settlements in the Csókakő domain

The primary OLC model was used to examine the 1,500 and 5,000 m buffer zones surrounding the 24 medieval and Early Modern settlements within the Csókakő domain. This analysis focused on the closer and wider ecological niches, as well as the potential economic roles of individual settlements.

Signs of ecological determinism are partially evident in the modelled results, stemming from the complex geographical landscape of the study area, which includes water bodies, lowlands, hilly terrain, and mountainous zones (Apronen et al. 2019; Lespez 2025).

Settlements within the Csókakő domain situated between Lake Velence and the Vértes Mountains (Kerekszenttamás, Fornaszentmiklós, Zámor, Pátka, Csala and Dinnyésméd) are characterised by arable land dominance, ranging from 35% to 66% of land cover types – indicating a primarily agricultural zone. The second most significant land cover is pasture, comprising 20–35%, while forests and swamps generally play a marginal role (**Fig. 1., 10., Table 2**).

Villages in the Mór Ditch (Csurgó, Igar, Szentgyörgy) and along the fringes of the Vértes (Mór, Vaja, Csókakő, Orond) and Bakony Mountains (Isztimér) display the most balanced distribution of land cover types. Lowland settlements are dominated by swamps, arable land, and forests, while those closer to the mountains are primarily surrounded by forests, arable land, or pastures – collectively accounting for 70–80% of land cover within the 1,500-metres buffer zones. In the wider 5,000-metres zones, the proportion of forests alone rises to over 40–60%, due to the proximity of extensive modelled forested areas in the mountains.

The influence of the Mór Wine District is most apparent in the buffer zones of nearby settlements. Vineyards account for 3–10% of land cover in the 1,500-metres zones, with reaching over 27% at Csókakő. However, the significant drop in vineyard coverage within the 5,000-metres zones (down to 1–7%) suggests these labour-intensive fields were easily accessible from the settlements, but spatially limited (**Fig. 10, Table 2**).

Table 1.: Comparison of land cover categories in the Second Military Survey and the primary optimal land cover model

1. táblázat: A Második Katonai Felmérés és az elsődleges optimális felszínborítottsági modell kategóriáinak összevetése

		land cover categories of the Second Military Survey							
		artificial	arable land	pasture	stream/wet pasture	vineyard	forest	swamp	***Sum***
land cover categories of the primary OLC	artificial	0	0	0	0	0	0	0	***0***
	arable land	0.83	19.84	2.68	0.81	0.5	4.77	0.14	***29.57***
	pasture	0.37	4.12	3.41	0.12	0.31	2.53	0.13	***11***
	stream/wet pasture	0.28	3.12	0.7	2.14	0.05	2.63	0.03	***8.96***
	vineyard	0.02	0.39	0.1	0.01	0.26	0.34	0	***1.13***
	forest	0.6	12.04	4.82	0.63	1.29	25.2	0	***44.59***
	swamp	0.03	1.56	0.8	0.18	0	0.01	2.16	***4.75***
Sum		***2.14***	***41.07***	***12.52***	***3.9***	***2.41***	***35.49***	***2.47***	***100***

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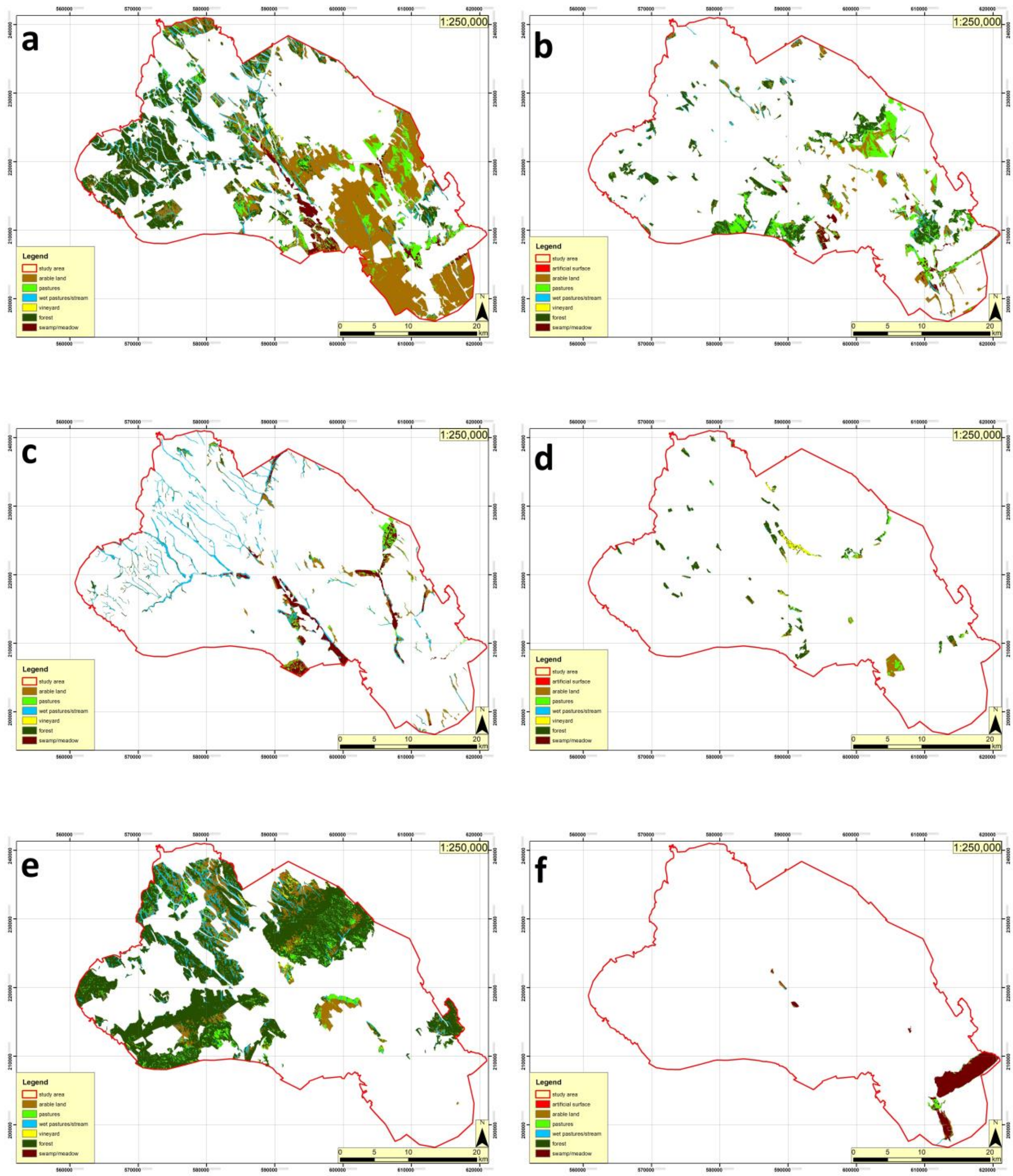

Fig. 7.: Optimal land cover modelling results of the different land covers recorded in the Second Military Survey. a, arable land, b, pastures, c, streams and wet pastures, d, vineyards, e, forests, f, swamps

7. ábra: A Második katonai felmérésen szereplő szántóterületek a, legelők b, vízfolyások és vizes gyepek c, szőlők d, erdők e, és mocsaras területek f, optimális felszínborítottsági modellezési eredményei.

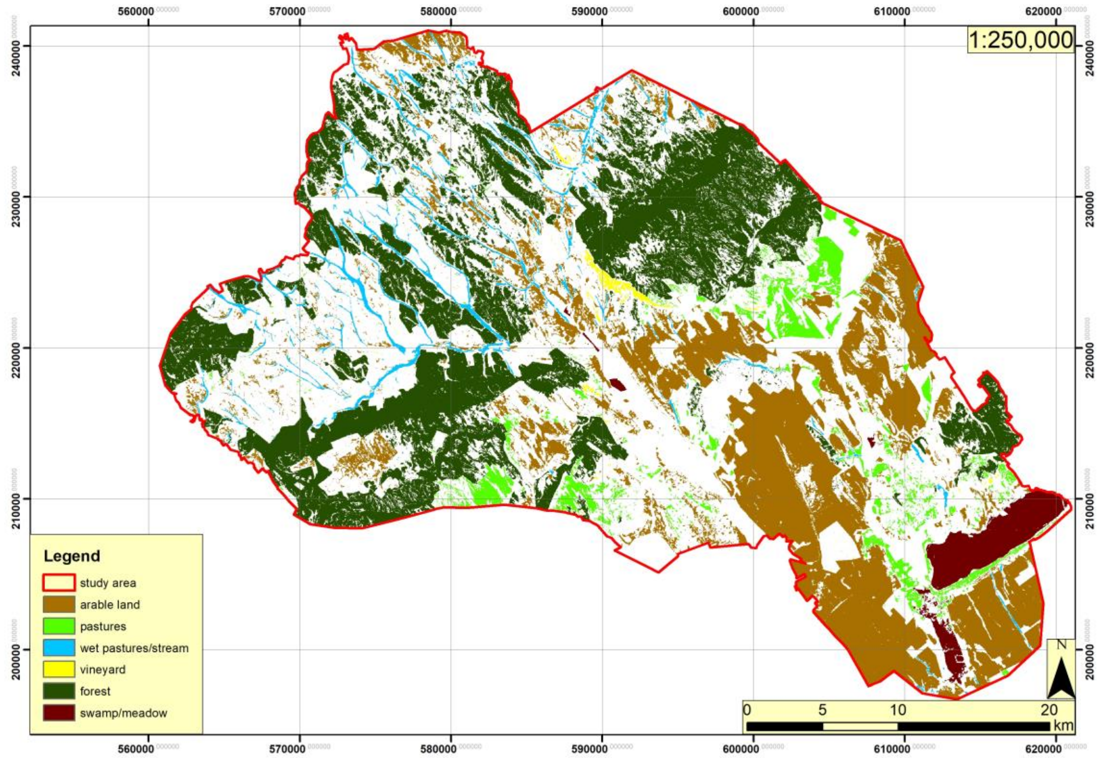

Fig. 8.: Identical land covers in the primary optimal land cover model and the Second Military Survey

8. ábra: Az elsődleges optimális felszínborítottsági modellen és a Második Katonai Felmérésen egyező felszínborítottságú területek

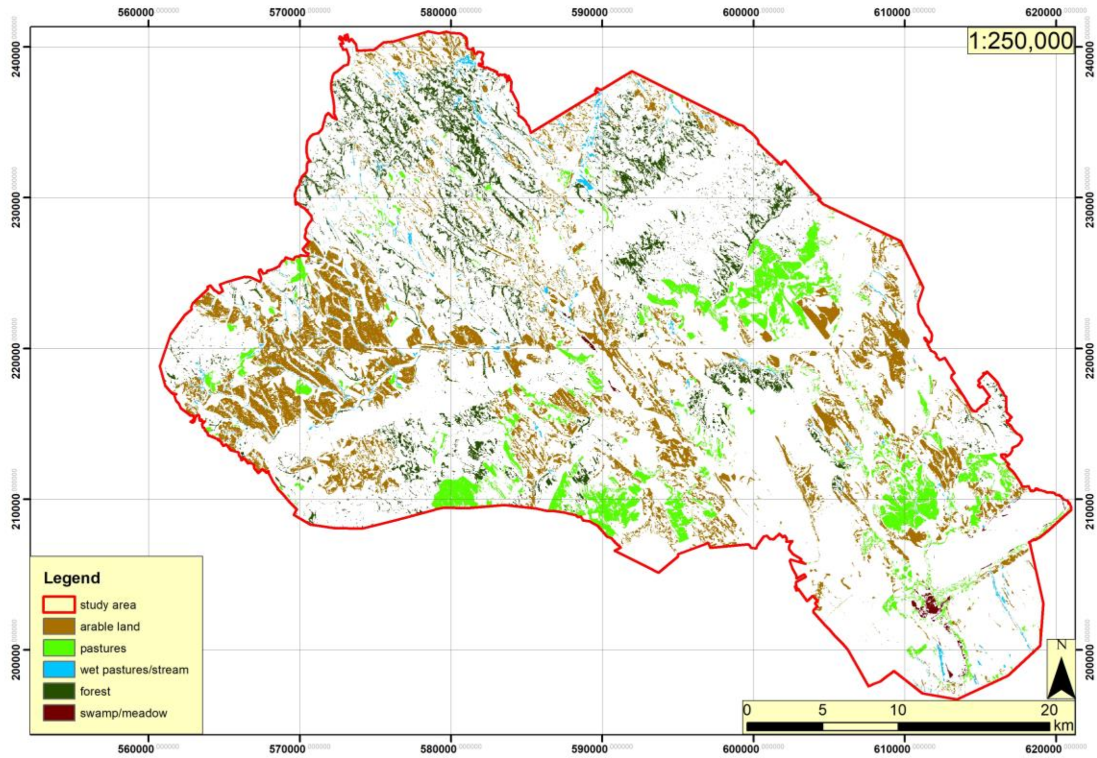

Fig. 9.: Identical land covers in the secondary optimal land cover model and the Second Military Survey

9. ábra: A másodlagos optimális felszínborítottsági modellen és a Második Katonai Felmérésen egyező felszínborítottságú területek

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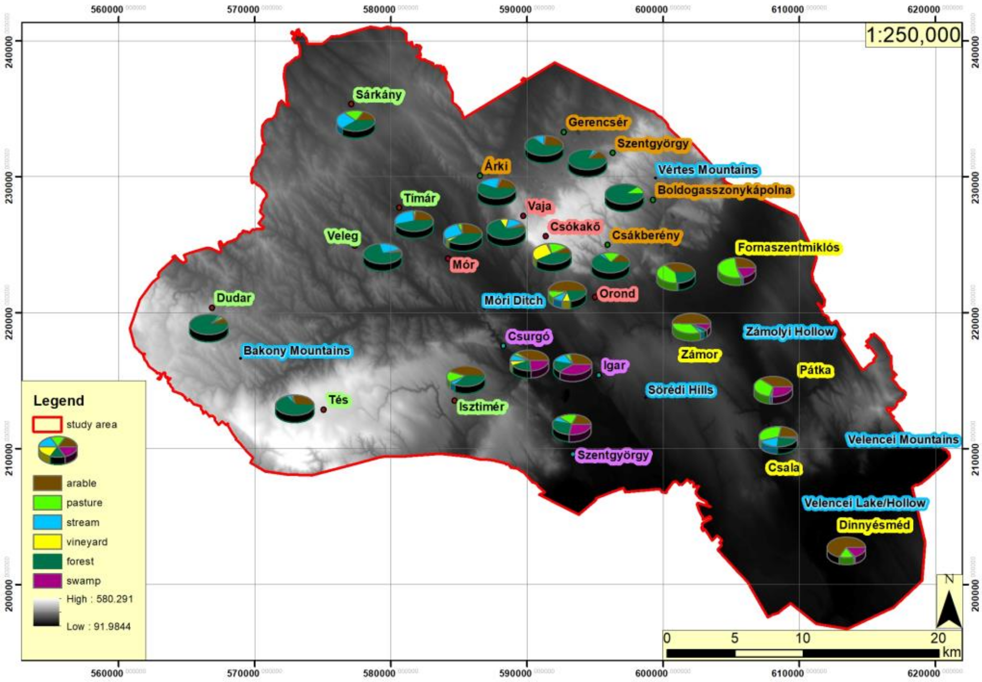

Fig. 10.: Distribution of land cover types in the 1,500-metre buffer zones of the known medieval settlements

10. ábra: Az ismert középkori települések 1500 méteres buffer zónájában található felszínborítottsági kategóriák összetétele

In the Vértes (Csákberény, Boldogasszonykápolna, Szentgyörgy, Gerencsér, Árki) and Bakony Mountains (Sárkány, Tímár, Veleg, Dudar, Tés), forests dominate the landscape, covering 40–90% of the settlement areas and generally exceeding 60%. Given their geographical locations, swamps and vineyards play a marginal role, while 10–25% of arable land is typically accessible in the immediate vicinity. Pastures are significant only around Csákberény, Boldogasszonykápolna, and Sárkány, where they represent approximately 10% of land cover. Local streams – covering 10–25% – are notably present on the lower northern slopes of the Bakony and Vértes Mountains (Veleg, Tímár, Sárkány, Árki, Gerencsér, Szentgyörgy) (**Fig. 10, Table 2**).

Model verification

Estimation from 1493 and the primary optimal land cover data around the settlements

In 1493, the Csókakő and Vitány castle domains were pledged, and a detailed perambulation was conducted to assess the lands of these domains (Bocsi 2024, 511–512; MOL OL DL 13455, 88167). The related estimation (*közbecsü* or *oklevél*) presents a unique opportunity to compare the modelling results with Late Medieval land cover, as it includes a detailed census of adjacent settlements (Csákberény, Csókakő, Csurgó, Igar, Mór, Sárkány, Tímár, Vaja, Veleg, Zámor, and [Kerék]-Szent-tamás), categorised by land cover types (arable land, pastures, meadows, vineyards, and forests).

It must be acknowledged that the medieval village boundaries and the 1,500- and 5,000-metres buffer zones (corresponding to approximately 7 and 78.5 km² of area, respectively) around the settlements differ, and no precise information currently exists on the exact layout of medieval landholdings or ownership. Furthermore, population size likely influenced the extent of cultivated fields, making a direct comparison problematic (**Table 3**).

A strong correlation is observable between the recorded 'population' (*sessio populosa*) of the villages ($R^2 = 0.7842$) and the extent of arable land ($R^2 = 0.8942$) (**Figs. 11–12**), relative to the total area of non-forested land (ranging from 0.84 to 9.28 km²). This indicates a relatively consistent ratio between field size, agricultural output, and available labour force – suggesting a stable, at least self-sufficient, agrarian economy. Nevertheless, diversification in land use is evident in the varied distribution of land cover types. As also indicated by the model, meadows and pastures appear near all settlements, likely serving as sources of fodder and occupying roughly 10% of each village's area (Champion 1979; Chisholm 1979b; Ponsard 1983).

At Csurgó and Igar, located on the periphery of the Mór Ditch lowlands, the proportion of pastures and meadows is highest (50–60%), which may correspond with the increased presence of swampy areas

Table 2.: Distribution of land cover types (km^2) in the 1,500- and 5000-metres buffer zones of the known medieval settlements. Accuracy of location: 1, on spot, 2, probable, 3, uncertain

2. táblázat: A különböző felszínborítottsági kategóriák megoszlása (km^2) az ismert középkori települések 1500 és 5000 méter sugarú buffer zónájában. (az azonosítás pontossága: 1 – pontos, 2 – valószínű, 3 – bizonytalan)

id	Medieval village	Accuracy of locali-zation	Site id HNSR	Modern settlement	Arable land (%)		Pasture (%)		Stream/wet pasture (%)		Vineyard (%)		Forest (%)		Swamp (%)	
					1500 m	5000 m	1500 m	5000 m	1500 m	5000 m	1500 m	5000 m	1500 m	5000 m	1500 m	5000 m
1	**Árki**	1	68373	Mór	19.17	20.63	1.88	2.64	22.78	18.72	0.15	3.24	55.99	54.28	0.04	0.49
2	**Boldogasszonykápolna**	1	98623	Gánt	0	5.97	10.75	10.49	0	1.66	0	0.00	89.25	81.84	0	0.04
3	**Csákberény**	1	97971	Csákberény	13.95	30.15	19.95	15.30	4.16	2.93	0.11	3.53	61.83	48.09	0	0.01
4	**Csala**	2	100183	Székesfehérvár	22.01	38.01	33	23.51	18.53	8.91	0.04	0.55	24.06	22.93	2.36	6.09
5	**Csókakő Várallya**	2	21791	Csókakő	8.82	22.06	20.14	8.90	1.81	6.63	27.2	7.19	42.03	52.11	0	3.11
6	**Csorgó**	1	21888	Fehérvárcsurgó	38.61	28.05	4.41	7.84	7.64	8.85	5.48	3.00	20.31	37.66	23.55	14.61
7	**Dinnyésméd**	1	57160	Gárdony	66.85	56.78	16.83	11.51	1.23	2.18	0	0.00	0.26	0.57	14.84	28.96
8	**Dudar**	1	7844	Dudar	7.8	5.90	3.49	2.85	3.19	8.94	0.06	0.46	85.44	81.84	0.01	0.00
9	**Fornaszentmiklós**	3	98043	Csákvár	26.99	36.58	52.61	41.04	2.7	1.57	0	0.12	0.2	10.54	17.5	10.14
10	**Gerencsér**	1	45879	Oroszlány	22.61	23.49	2.5	2.27	10.96	10.28	2.36	2.38	61.31	60.41	0.25	1.16
11	**Igar**	2	93113	Fehérvárcsurgó	28.18	38.76	5.26	9.13	12.86	8.80	0.09	1.58	14.24	23.18	39.38	18.55
12	**Isztimér**	1	21937	Isztimér	44.26	16.11	13.07	13.33	5.27	6.48	0.01	2.14	37.39	60.27	0	1.68
13	**Kerekszenttamás**	1	22431	Zámoly	37.6	31.89	38.28	32.15	0.48	2.79	1.5	0.43	22.14	29.38	0	3.36
14	**Mór**	1	39132	Mór	26.11	25.10	5.73	4.25	24.61	19.34	3.46	4.24	40.07	45.10	0.02	1.97
15	**Orond**	3	49416	Söréd	49.94	39.85	9.15	9.96	9.83	6.48	9.92	6.61	21.17	30.17	0	6.93
16	**Pátka**	1	22096	Pátka	38.8	49.37	31.03	21.21	3.11	7.71	0.28	0.72	0.86	15.40	25.92	5.59
17	**Sárkány**	2	64012	Bakonysárkány	16.25	24.17	21.63	9.95	22.47	23.18	0	0.05	39.64	42.63	0.02	0.01
18	**Szentgyörgy**	3	89419	Oroszlány	12.22	15.26	1.99	4.23	4.72	5.12	0	1.86	81.04	73.30	0.03	0.22
19	**Szentgyörgy**	3	22486	Iszkaszentgyörgy	18.58	19.56	21.26	16.61	6.03	7.05	0	1.04	26.15	29.47	27.98	26.27
20	**Tés**	1	9411	Tés	27.3	11.62	2.45	4.18	4.6	5.34	0	0.45	65.65	78.41	0	0.01
21	**Tímár**	1	68315	Mór	22.65	22.38	2.87	3.91	28.39	24.60	0.11	0.51	45.97	48.50	0	0.11
22	**Vaja**	3	98603	Mór	4.6	23.85	2.04	5.44	15.7	15.34	10.41	5.81	67.26	47.33	0	2.23
23	**Veleg**	1	98851	Nagyveleg	3.03	10.76	1.76	2.44	24.25	20.34	0.04	0.58	70.92	65.68	0	0.19
24	**Zámor**	1	22432	Zámoly	49.28	60.87	34.95	26.38	4.18	2.45	0.85	0.41	3.02	3.99	7.72	5.90

Table 3.: Proportion and size of land cover types based on the 1493 estimation

3. táblázat: A felszínborítottsági kategóriák aránya és mérete az 1493-as közbecsű jegyzékben

		size (km^2)					**proportion per settlement area (with forests - %)**					**Sum (km^2)**	**proportion per settlement area (without forests - %)**				**Size (km^2)**
settlement	**sessio populosa**	**meadow**	**arable land**	**pasture**	**vineyard**	**forest**	**meadow**	**arable land**	**pasture**	**vineyard**	**forest**		**meadow**	**arable land**	**pasture**	**vineyard**	
Csókakő	8	0.34	1.27	0.63	0.03	3.80	5.56	20.86	10.43	0.56	62.59	**6.07**	14.87	55.76	27.88	1.49	**2.27**
Csurgó	24	1.16	1.90	1.27	0.17	0.42	23.54	38.66	25.77	3.44	8.59	**4.91**	25.75	42.29	28.20	3.76	**4.49**
Igar	14	2.21	1.48	0.19	0	0	57.08	38.13	4.79	0	0	**3.87**	57.08	38.13	4.79	0	**3.87**
Mór	48	0.34	7.60	1.27	0.08	3.80	2.58	58.06	9.68	0.65	29.03	**13.08**	3.64	81.82	13.64	0.91	**9.28**
Sárkány	7	1.27	2.53	0	0	13.93	7.14	14.29	0	0	78.57	**17.72**	33.33	66.67	0	0	**3.80**
Tímár	20	1.37	5.06	0	0	7.60	9.75	36.10	0	0	54.15	**14.03**	21.26	78.74	0	0	**6.43**
Vaja	15	0	1.27	0.17	0.17	0	0	78.95	10.53	10.53	0	**1.60**	0	78.95	10.53	10.53	**1.60**
Veleg	4	0.20	0.63	0	0	12.66	1.50	4.69	0	0	93.81	**13.50**	24.24	75.76	0	0	**0.84**
Zámor and Szenttamás	18	0.68	2.53	2.53	0.03	10.13	4.25	15.93	15.93	0.16	63.73	**15.89**	11.71	43.92	43.92	0.44	**5.76**
Sum	**158**	**7.55**	**24.27**	**6.05**	**0.48**	**52.33**						**90.68**					**38.35**

predicted by the model. The proportion of arable land in these two settlements, as well as in Zámoly and [Kerék]Szenttamás, is notably lower (~40% of non-forested land) than in the other settlements, where it ranges from approximately 55% to 81% (of non-forested land).

Estimation data also aligns with the model in identifying the main wine-producing settlements in the microregion (Csókakő, Csurgó, Mór, Vaja, Zámor, and [Kerék]Szenttamás).

Vineyard areas within the 1,500-metres buffer zones correspond closely with those documented in the estimation, except at Csókakő, where the model likely overestimates vineyard extent due to the discrepancy between the actual medieval village boundaries and the buffer zone. Among the nine analysed settlements, those associated with viticulture generally had smaller land holdings, which may be attributed to the labour-intensive nature of vineyard maintenance.

When forests are considered, additional patterns emerge in Sárkány, Tímár, and Veleg, where forests cover 54–93% of land within the settlement boundaries, closely matching the modelled OLC proportions. Excluding the pasture-dominated Csurgó and Igar, a strong negative correlation is observable in the remaining settlements (Csókakő, Mór, Sárkány, Tímár, Vaja, Veleg, Zámor, and [Kerék]Szenttamás) between arable land and forest cover. The estimation data yield an R^2 value of 0.8932 (excluding Csurgó and Igar), which closely mirrors the modelled correlation ($R^2 = 0.7868$), although the model tends to slightly overestimate the proportion of streams (**Figs. 13–14**).

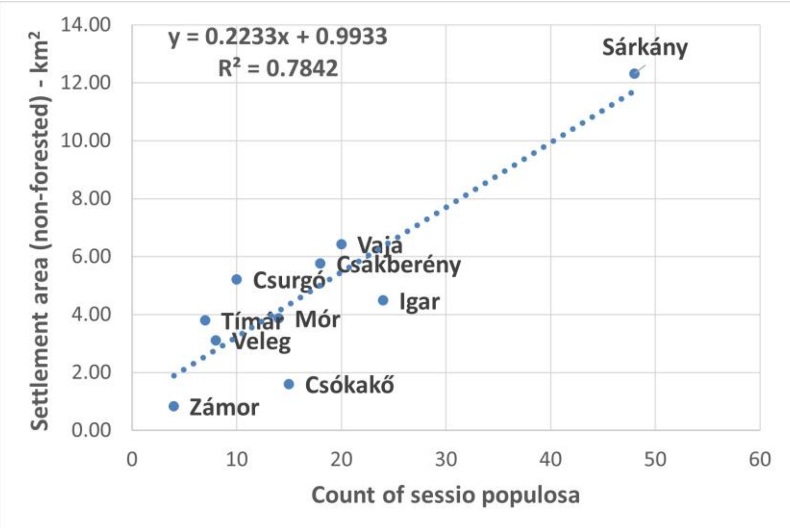

Fig. 11.: Connection between the *sessio populosa* and settlement size (non-forested area) based on the 1493 estimation

11. ábra: A lakott jobbágytelkek és a települések erdők nélkül számított területének kapcsolata az 1493-as közbecsü adatai alapján

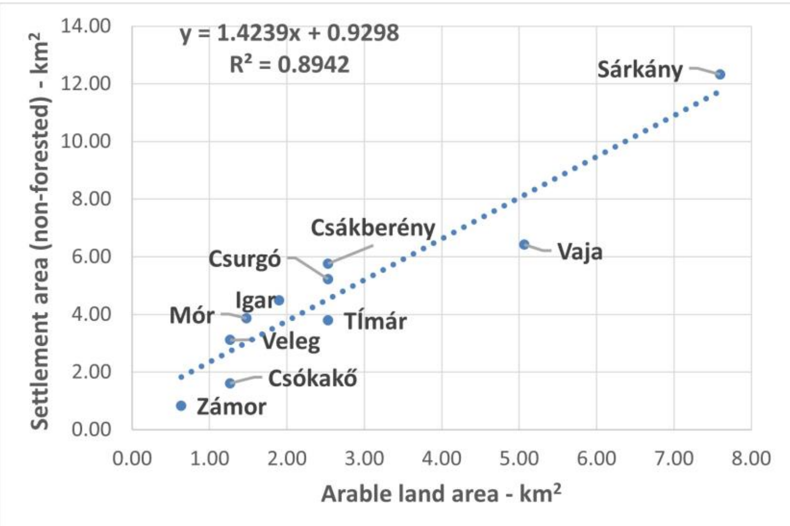

Fig. 12.: Connection between arable land and settlement size (non-forested area) based on the 1493 estimation

12. ábra: A településekhez tartozó szántóterületek és a települések erdők nélkül számított területének aránya az 1493-as közbecsü adatai alapján

Table 4.: Proportion of land cover types in the study area
4. táblázat: A felszínborítottsági típusok megoszlása a kutatási területen

Land cover	Second Military Survey (~1847)	Primary OLC	Estimation - 1493	Corine LC 2000
artificial	2.13	-	-	6.06
arable land	40.43	29.57	40	46.13
vineyard	2.38	1.13		1.95
pasture	12.03	11	16	6.76
stream/wet pasture	7.23	8.96	10	1.39
swamp	2.31	4.75		1.95
forest	33.5	44.59	34	35.75
Sum	100	100	100	100

Further data verification

To further validate the modelled OLC data, it is useful to compare the results of the OLC modelling and the land cover categories derived from the Second Military Survey with datasets from 15th-century public registries (*közbecsű jegyzék*) of the Kingdom of Hungary (Szabó 2006). These historical datasets, currently covering approximately 1% of the Kingdom's territory, are spatially uneven and primarily concentrated in forest-rich, hilly, and mountainous areas; therefore, they must be interpreted with caution.

Nevertheless, the national-level summary of land cover types in the 15th-century public registries reveals patterns broadly consistent with those observed in the study area during the Second Military Survey. Furthermore, when these proportions are placed in broader context, they align with the satellite-based CORINE Land Cover database (1:100,000 scale, 2000), which reflects similar land use patterns in the region – albeit with a slightly higher proportion of arable land (https://doi.org/10.2909/ddacbd5e-068f-4e52-a596-d606e8de7f40; last accessed on 24. 04. 2025.) (**Table 4**).

It is important to emphasise that roughly two-thirds of the study area lies within the Vértes, Bakony, and Velence Mountains, where the modelled high percentage of forest cover may more accurately represent the medieval and Early Modern periods, during which arable lands were likely less extensive than in the 19th century. Supporting this interpretation, public registry data from neighbouring Veszprém County indicate 60–75% forest cover, while Esztergom County shows a somewhat lower range of 20–40% (Szabó 2006).

Conclusions

In recent decades, the study of land cover and land use changes has received growing attention in archaeological research as a means of better understanding the everyday activities, economic opportunities, and environmental constraints that shaped past societies. The approach presented here integrates GIS-based analysis of environmental layers (geology, pedology, topographic wetness index, landform classification, aspect) with land cover data derived from the early 19th-century Second Military Survey, to generate historically grounded land cover models for the Middle Ages and the Early Modern Period.

The modelling results clearly suggest that settlements within the Csókakő domain formed part of an integrated system structured both by the authority of the castle and the surrounding environmental conditions. Written sources and modelled data alike point to notable shifts in land cover distribution within the domain, indicating that villages likely fulfilled specific roles within the regional landscape. At the same time, each settlement appears to have maintained a degree of self-sufficiency, ensured by a baseline allocation of arable land and pasture or meadow for crop production and animal husbandry. The analysis of local, village-based land cover patterns offers a future output for the modelling by integrating environmental datasets, historical sources and theoretical considerations (Ferenczi & Vargha 2024).

Environmental factors shaped the location and development of specialised economic activities, such as viticulture (Csókakő, Csurgó, Mór, Vaja), forestry (Sárkány, Tímár, Veleg), crop cultivation

(Csurgó, Igar, Mór, Tímár, Zámor), and animal husbandry (Csókakő, Csurgó, Igar, Sárkány, Zámor). The strong correspondence between the medieval written sources and the modelled optimal land cover (OLC) data reinforces the value of spatially precise historical land cover reconstructions in interpreting the dynamics of medieval and early modern rural economies.

Contribution of authors

Gábor Mesterházy Writing – Original Draft, Review & Editing.

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